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Distribution Systems

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- 20 Power System Loads** *Raymond R. Shoults and Larry D. Swift* 20-1
Load Classification • Modeling Applications • Load Modeling Concepts
and Approaches • Load Characteristics and Models • Static
Load Characteristics • Load Window Modeling
- 21 Distribution System Modeling and Analysis** *William H. Kersting* 21-1
Modeling • Analysis
- 22 Power System Operation and Control** *George L. Clark and Simon W. Bowen* 22-1
Implementation of Distribution Automation • Distribution SCADA
History • Field Devices • Integrated SCADA System • Security • Practical
Considerations • Standards • Deployment Considerations
- 23 Hard to Find Information (on Distribution System Characteristics
and Protection)** *Jim Burke* 23-1
Overcurrent Protection • Transformers • Instrument Transformers • Loading •
Miscellaneous Loading Information
- 24 Real-Time Control of Distributed Generation** *Murat Dilek and
Robert P. Broadwater* 24-1
Local Site DG Control • Hierarchical Control: Real-Time Control •
Control of DGs at Circuit Level • Hierarchical Control: Forecasting Generation

20

Power System Loads

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20.1	Load Classification	20-1
20.2	Modeling Applications.....	20-2
20.3	Load Modeling Concepts and Approaches	20-3
20.4	Load Characteristics and Models.....	20-3
20.5	Static Load Characteristics	20-5
	Exponential Models • Polynomial Models • Combined Exponential and Polynomial Models • Comparison of Exponential and Polynomial Models • Devices Contributing to Modeling Difficulties	
20.6	Load Window Modeling.....	20-9

The physical structure of most power systems consists of generation facilities feeding bulk power into a high-voltage bulk transmission network, that in turn serves any number of distribution substations. A typical distribution substation will serve from one to as many as ten feeder circuits. A typical feeder circuit may serve numerous loads of all types. A light to medium industrial customer may take service from the distribution feeder circuit primary, while a large industrial load complex may take service directly from the bulk transmission system. All other customers, including residential and commercial, are typically served from the secondary of distribution transformers that are in turn connected to a distribution feeder circuit. [Figure 20.1](#) illustrates a representative portion of a typical configuration.

20.1 Load Classification

The most common classification of electrical loads follows the billing categories used by the utility companies. This classification includes residential, commercial, industrial, and other. Residential customers are domestic users, whereas commercial and industrial customers are obviously business and industrial users. Other customer classifications include municipalities, state and federal government agencies, electric cooperatives, educational institutions, etc.

Although these load classes are commonly used, they are often inadequately defined for certain types of power system studies. For example, some utilities meter apartments as individual residential customers, while others meter the entire apartment complex as a commercial customer. Thus, the common classifications overlap in the sense that characteristics of customers in one class are not unique to that class. For this reason some utilities define further subdivisions of the common classes.

A useful approach to classification of loads is by breaking down the broader classes into individual load components. This process may altogether eliminate the distinction of certain of the broader classes, but it is a tried and proven technique for many applications. The components of a particular load, be it residential, commercial, or industrial, are individually defined and modeled. These load components as a whole constitute the composite load and can be defined as a “load window.”

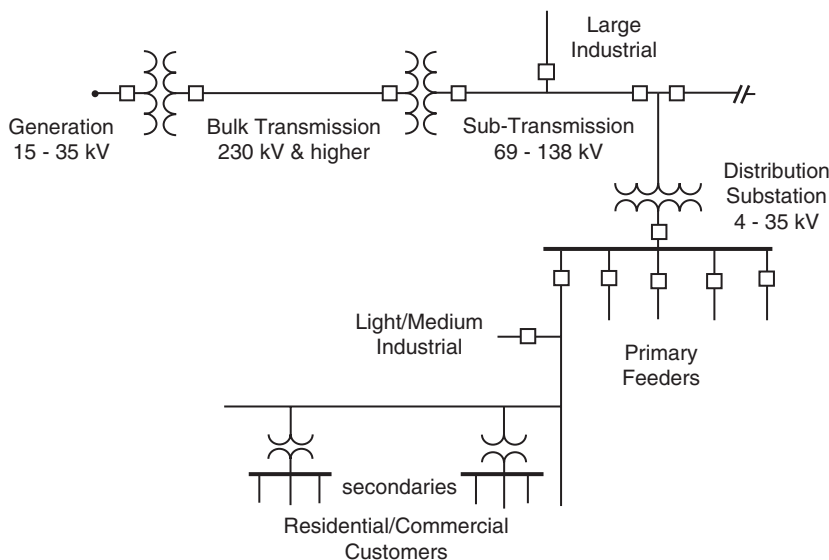


FIGURE 20.1 Representative portion of a typical power system configuration.

20.2 Modeling Applications

It is helpful to understand the applications of load modeling before discussing particular load characteristics. The applications are divided into two broad categories: static (“snap-shot” with respect to time) and dynamic (time varying). Static models are based on the steady-state method of representation in power flow networks. Thus, static load models represent load as a function of voltage magnitude. Dynamic models, on the other hand, involve an alternating solution sequence between a time-domain solution of the differential equations describing electromechanical behavior and a steady-state power flow solution based on the method of phasors. One of the important outcomes from the solution of dynamic models is the time variation of frequency. Therefore, it is altogether appropriate to include a component in the static load model that represents variation of load with frequency. The lists below include applications outside of Distribution Systems but are included because load modeling at the distribution level is the fundamental starting point.

Static applications: Models that incorporate only the voltage-dependent characteristic include the following.

- Power flow (PF)
 - Distribution power flow (DPF)
 - Harmonic power flow (HPF)
 - Transmission power flow (TPF)
- Voltage stability (VS)

Dynamic applications: Models that incorporate both the voltage- and frequency-dependent characteristics include the following.

- Transient stability (TS)
- Dynamic stability (DS)
- Operator training simulators (OTS)

Strictly power-flow based solutions utilize load models that include only voltage dependency characteristics. Both voltage and frequency dependency characteristics can be incorporated in load modeling for those hybrid methods that alternate between a time-domain solution and a power flow solution,

such as found in Transient Stability and Dynamic Stability Analysis Programs, and Operator Training Simulators.

Load modeling in this section is confined to static representation of voltage and frequency dependencies. The effects of rotational inertia (electromechanical dynamics) for large rotating machines are discussed in [Chapters 11](#) and [12](#). Static models are justified on the basis that the transient time response of most composite loads to voltage and frequency changes is fast enough so that a steady-state response is reached very quickly.

20.3 Load Modeling Concepts and Approaches

There are essentially two approaches to load modeling: component based and measurement based. Load modeling research over the years has included both approaches (EPRI, 1981; 1984; 1985). Of the two, the component-based approach lends itself more readily to model generalization. It is generally easier to control test procedures and apply wide variations in test voltage and frequency on individual components.

The component-based approach is a “bottom-up” approach in that the different load component types comprising load are identified. Each load component type is tested to determine the relationship between real and reactive power requirements versus applied voltage and frequency. A load model, typically in polynomial or exponential form, is then developed from the respective test data. The range of validity of each model is directly related to the range over which the component was tested. For convenience, the load model is expressed on a per-unit basis (i.e., normalized with respect to rated power, rated voltage, rated frequency, rated torque if applicable, and base temperature if applicable). A composite load is approximated by combining appropriate load model types in certain proportions based on load survey information. The resulting composition is referred to as a “load window.”

The measurement approach is a “top-down” approach in that measurements are taken at either a substation level, feeder level, some load aggregation point along a feeder, or at some individual load point. Variation of frequency for this type of measurement is not usually performed unless special test arrangements can be made. Voltage is varied using a suitable means and the measured real and reactive power consumption recorded. Statistical methods are then used to determine load models. A load survey may be necessary to classify the models derived in this manner. The range of validity for this approach is directly related to the realistic range over which the tests can be conducted without damage to customers’ equipment. Both the component and measurement methods were used in the EPRI research projects EL-2036 (1981) and EL-3591 (1984–85). The component test method was used to characterize a number of individual load components that were in turn used in simulation studies. The measurement method was applied to an aggregate of actual loads along a portion of a feeder to verify and validate the component method.

20.4 Load Characteristics and Models

Static load models for a number of typical load components appear in [Tables 20.1](#) and [20.2](#) (EPRI 1984–85). The models for each component category were derived by computing a weighted composite from test results of two or more units per category. These component models express per-unit real power and reactive power as a function of per-unit incremental voltage and/or incremental temperature and/or per-unit incremental torque. The incremental form used and the corresponding definition of variables are outlined below:

$$\Delta V = V_{\text{act}} - 1.0 \text{ (incremental voltage in per unit)}$$

$$\Delta T = T_{\text{act}} - 95^{\circ}\text{F} \text{ (incremental temperature for Air Conditioner model)}$$

$$= T_{\text{act}} - 47^{\circ}\text{F} \text{ (incremental temperature for Heat Pump model)}$$

$$\Delta \tau = \tau_{\text{act}} - \tau_{\text{rated}} \text{ (incremental motor torque, per unit)}$$

TABLE 20.1 Static Models of Typical Load Components—AC, Heat Pump, and Appliances

Load Component	Static Component Model
1- ϕ Central Air Conditioner	$P = 1.0 + 0.4311*\Delta V + 0.9507*\Delta T + 2.070*\Delta V^2 + 2.388*\Delta T^2 - 0.900*\Delta V*\Delta T$ $Q = 0.3152 + 0.6636*\Delta V + 0.543*\Delta V^2 + 5.422*\Delta V^3 + 0.839*\Delta T^2 - 1.455*\Delta V*\Delta T$
3- ϕ Central Air Conditioner	$P = 1.0 + 0.2693*\Delta V + 0.4879*\Delta T + 1.005*\Delta V^2 - 0.188*\Delta T^2 - 0.154*\Delta V*\Delta T$ $Q = 0.6957 + 2.3717*\Delta V + 0.0585*\Delta T + 5.81*\Delta V^2 + 0.199*\Delta T^2 - 0.597*\Delta V*\Delta T$
Room Air Conditioner (115V Rating)	$P = 1.0 + 0.2876*\Delta V + 0.6876*\Delta T + 1.241*\Delta V^2 + 0.089*\Delta T^2 - 0.558*\Delta V*\Delta T$ $Q = 0.1485 + 0.3709*\Delta V + 1.5773*\Delta T + 1.286*\Delta V^2 + 0.266*\Delta T^2 - 0.438*\Delta V*\Delta T$
Room Air Conditioner (208/230V Rating)	$P = 1.0 + 0.5953*\Delta V + 0.5601*\Delta T + 2.021*\Delta V^2 + 0.145*\Delta T^2 - 0.491*\Delta V*\Delta T$ $Q = 0.4968 + 2.4456*\Delta V + 0.0737*\Delta T + 8.604*\Delta V^2 - 0.125*\Delta T^2 - 1.293*\Delta V*\Delta T$
3- ϕ Heat Pump (Heating Mode)	$P = 1.0 + 0.4539*\Delta V + 0.2860*\Delta T + 1.314*\Delta V^2 - 0.024*\Delta V*\Delta T$ $Q = 0.9399 + 3.013*\Delta V - 0.1501*\Delta T + 7.460*\Delta V^2 - 0.312*\Delta T^2 - 0.216*\Delta V*\Delta T$
3- ϕ Heat Pump (Cooling Mode)	$P = 1.0 + 0.2333*\Delta V + 0.5915*\Delta T + 1.362*\Delta V^2 + 0.075*\Delta T^2 - 0.093*\Delta V*\Delta T$ $Q = 0.8456 + 2.3404*\Delta V - 0.1806*\Delta T + 6.896*\Delta V^2 + 0.029*\Delta T^2 - 0.836*\Delta V*\Delta T$
1- ϕ Heat Pump (Heating Mode)	$P = 1.0 + 0.3953*\Delta V + 0.3563*\Delta T + 1.679*\Delta V^2 + 0.083*\Delta V*\Delta T$ $Q = 0.3427 + 1.9522*\Delta V - 0.0958*\Delta T + 6.458*\Delta V^2 - 0.225*\Delta T^2 - 0.246*\Delta V*\Delta T$
1- ϕ Heat Pump (Cooling Mode)	$P = 1.0 + 0.3630*\Delta V + 0.7673*\Delta T + 2.101*\Delta V^2 + 0.122*\Delta T^2 - 0.759*\Delta V*\Delta T$ $Q = 0.3605 + 1.6873*\Delta V + 0.2175*\Delta T + 10.055*\Delta V^2 - 0.170*\Delta T^2 - 1.642*\Delta V*\Delta T$
Refrigerator	$P = 1.0 + 1.3958*\Delta V + 9.881*\Delta V^2 + 84.72*\Delta V^3 + 293*\Delta V^4$ $Q = 1.2507 + 4.387*\Delta V + 23.801*\Delta V^2 + 1540*\Delta V^3 + 555*\Delta V^4$
Freezer	$P = 1.0 + 1.3286*\Delta V + 12.616*\Delta V^2 + 133.6*\Delta V^3 + 380*\Delta V^4$ $Q = 1.3810 + 4.6702*\Delta V + 27.276*\Delta V^2 + 293.0*\Delta V^3 + 995*\Delta V^4$
Washing Machine	$P = 1.0 + 1.2786*\Delta V + 3.099*\Delta V^2 + 5.939*\Delta V^3$ $Q = 1.6388 + 4.5733*\Delta V + 12.948*\Delta V^2 + 55.677*\Delta V^3$
Clothes Dryer	$P = 1.0 - 0.1968*\Delta V - 3.6372*\Delta V^2 - 28.32*\Delta V^3$ $Q = 0.209 + 0.5180*\Delta V + 0.363*\Delta V^2 - 4.7574*\Delta V^3$
Television	$P = 1.0 + 1.2471*\Delta V + 0.562*\Delta V^2$ $Q = 0.2431 + 0.9830*\Delta V + 1.647*\Delta V^2$
Fluorescent Lamp	$P = 1.0 + 0.6534*\Delta V - 1.65*\Delta V^2$ $Q = -0.1535 - 0.0403*\Delta V + 2.734*\Delta V^2$
Mercury Vapor Lamp	$P = 1.0 + 0.1309*\Delta V + 0.504*\Delta V^2$ $Q = -0.2524 + 2.3329*\Delta V + 7.811*\Delta V^2$
Sodium Vapor Lamp	$P = 1.0 + 0.3409*\Delta V - 2.389*\Delta V^2$ $Q = 0.060 + 2.2173*\Delta V + 7.620*\Delta V^2$
Incandescent	$P = 1.0 + 1.5209*\Delta V + 0.223*\Delta V^2$ $Q = 0.0$
Range with Oven	$P = 1.0 + 2.1018*\Delta V + 5.876*\Delta V^2 + 1.236*\Delta V^3$ $Q = 0.0$
Microwave Oven	$P = 1.0 + 0.0974*\Delta V + 2.071*\Delta V^2$ $Q = 0.2039 + 1.3130*\Delta V + 8.738*\Delta V^2$
Water Heater	$P = 1.0 + 0.3769*\Delta V + 2.003*\Delta V^2$ $Q = 0.0$
Resistance Heating	$P = 1.0 + 2*\Delta V + \Delta V^2$ $Q = 0.0$

If ambient temperature is known, it can be used in the applicable models. If it is not known, the temperature difference, ΔT , can be set to zero. Likewise, if motor load torque is known, it can be used in the applicable models. If it is not known, the torque difference, $\Delta \tau$, can be set to zero.

Based on the test results of load components and the developed real and reactive power models as presented in these tables, the following comments on the reactive power models are important.

- The reactive power models vary significantly from manufacturer to manufacturer for the same component. For instance, four load models of single-phase central air-conditioners show a Q/P ratio that varies between 0 and 0.5 at 1.0 p.u. voltage. When the voltage changes, the $\Delta Q/\Delta V$ of each unit is quite different. This situation is also true for all other components, such as refrigerators, freezers, fluorescent lights, etc.

TABLE 20.2 Static Models of Typical Load Components—Transformers and Induction Motors

Load Component	Static Component Model
Transformer	
Core Loss Model	$P = \frac{\text{KVA}(\text{rating})}{\text{KVA}(\text{systembase})} [0.00267V^2 + 0.73 \times 10^{-9} \times e^{13.5V^2}]$ $Q = \frac{\text{KVA}(\text{rating})}{\text{KVA}(\text{systembase})} [0.00167V^2 + 0.268 \times 10^{-13} \times e^{22.76V^2}]$ where V is voltage magnitude in per unit
1- ϕ Motor	$P = 1.0 + 0.5179*\Delta V + 0.9122*\Delta\tau + 3.721*\Delta V^2 + 0.350*\Delta\tau^2 - 1.326*\Delta V*\Delta\tau$
Constant Torque	$Q = 0.9853 + 2.7796*\Delta V + 0.0859*\Delta\tau + 7.368*\Delta V^2 + 0.218*\Delta\tau^2 - 1.799*\Delta V*\Delta\tau$
3- ϕ Motor (1–10HP)	$P = 1.0 + 0.2250*\Delta V + 0.9281*\Delta\tau + 0.970*\Delta V^2 + 0.086*\Delta\tau^2 - 0.329*\Delta V*\Delta\tau$
Const. Torque	$Q = 0.7810 + 2.3532*\Delta V + 0.1023*\Delta\tau - 5.951*\Delta V^2 + 0.446*\Delta\tau^2 - 1.48*\Delta V*\Delta\tau$
3- ϕ Motor (10HP/Above)	$P = 1.0 + 0.0199*\Delta V + 1.0463*\Delta\tau + 0.341*\Delta V^2 + 0.116*\Delta\tau^2 - 0.457*\Delta V*\Delta\tau$
Const. Torque	$Q = 0.6577 + 1.2078*\Delta V + 0.3391*\Delta\tau + 4.097*\Delta V^2 + 0.289*\Delta\tau^2 - 1.477*\Delta V*\Delta\tau$
1- ϕ Motor	$P = 1.0 + 0.7101*\Delta V + 0.9073*\Delta\tau + 2.13*\Delta V^2 + 0.245*\Delta\tau^2 - 0.310*\Delta V*\Delta\tau$
Variable Torque	$Q = 0.9727 + 2.7621*\Delta V + 0.077*\Delta\tau + 6.432*\Delta V^2 + 0.174*\Delta\tau^2 - 1.412*\Delta V*\Delta\tau$
3- ϕ Motor (1–10HP)	$P = 1.0 + 0.3122*\Delta V + 0.9286*\Delta\tau + 0.489*\Delta V^2 + 0.081*\Delta\tau^2 - 0.079*\Delta V*\Delta\tau$
Variable Torque	$Q = 0.7785 + 2.3648*\Delta V + 0.1025*\Delta\tau + 5.706*\Delta V^2 + 0.13*\Delta\tau^2 - 1.00*\Delta V*\Delta\tau$
3- ϕ Motor (10HP & Above)	$P = 1.0 + 0.1628*\Delta V + 1.0514*\Delta\tau \angle 0.099*\Delta V^2 + 0.107*\Delta\tau^2 + 0.061*\Delta V*\Delta\tau$
Variable Torque	$Q = 0.6569 + 1.2467*\Delta V + 0.3354*\Delta\tau + 3.685*\Delta V^2 + 0.258*\Delta\tau^2 - 1.235*\Delta V*\Delta\tau$

- It has been observed that the reactive power characteristic of fluorescent lights not only varies from manufacturer to manufacturer, from old to new, from long tube to short tube, but also varies from capacitive to inductive depending upon applied voltage and frequency. This variation makes it difficult to obtain a good representation of the reactive power of a composite system and also makes it difficult to estimate the $\Delta Q/\Delta V$ characteristic of a composite system.
- The relationship between reactive power and voltage is more non-linear than the relationship between real power and voltage, making Q more difficult to estimate than P.
- For some of the equipment or appliances, the amount of Q required at the nominal operating voltage is very small; but when the voltage changes, the change in Q with respect to the base Q can be very large.
- Many distribution systems have switchable capacitor banks either at the substations or along feeders. The composite Q characteristic of a distribution feeder is affected by the switching strategy used in these banks.

20.5 Static Load Characteristics

The component models appearing in [Tables 20.1](#) and 20.2 can be combined and synthesized to create other more convenient models. These convenient models fall into two basic forms: exponential and polynomial.

20.5.1 Exponential Models

The exponential form for both real and reactive power is expressed in Eqs. (20.1) and (20.2) below as a function of voltage and frequency, relative to initial conditions or base values. Note that neither temperature nor torque appear in these forms. Assumptions must be made about temperature and/or torque values when synthesizing from component models to these exponential model forms.

$$P = P_o \left[\frac{V}{V_o} \right]^{\alpha_v} \left[\frac{f}{f_o} \right]^{\alpha_f} \quad (20.1)$$

$$Q = Q_o \left[\frac{V}{V_o} \right]^{\beta_v} \left[\frac{f}{f_o} \right]^{\beta_f} \quad (20.2)$$

The per-unit models of Eqs. (20.1) and (20.2) are as follows.

$$P_u = \frac{P}{P_o} = \left[\frac{V}{V_o} \right]^{\alpha_v} \left[\frac{f}{f_o} \right]^{\alpha_f} \quad (20.3)$$

$$Q_u = \frac{Q}{P_o} = \frac{Q_o}{P_o} \left[\frac{V}{V_o} \right]^{\beta_v} \left[\frac{f}{f_o} \right]^{\beta_f} \quad (20.4)$$

The ratio Q_o/P_o can be expressed as a function of power factor (pf) where $\pm$ indicates a lagging/leading power factor, respectively.

$$R = \frac{Q_o}{P_o} = \pm \sqrt{\frac{1}{\text{pf}^2} - 1}$$

After substituting R for Q_o/P_o , Eq. (20.4) becomes the following.

$$Q_u = R \left[\frac{V}{V_o} \right]^{\beta_v} \left[\frac{f}{f_o} \right]^{\beta_f} \quad (20.5)$$

Equations (20.1) and (20.2) [or (20.3) and (20.5)] are valid over the voltage and frequency ranges associated with tests conducted on the individual components from which these exponential models are derived. These ranges are typically $\pm 10\%$ for voltage and $\pm 2.5\%$ for frequency. The accuracy of these models outside the test range is uncertain. However, one important factor to note is that in the extreme case of voltage approaching zero, both P and Q approach zero.

EPRI-sponsored research resulted in model parameters such as found in Table 20.3 (EPRI, 1987; Price et al., 1988). Eleven model parameters appear in this table, of which the exponents α and β and the power factor (pf) relate directly to Eqs. (20.3) and (20.5). The first six parameters relate to general load models, some of which include motors, and the remaining five parameters relate to nonmotor loads—typically resistive type loads. The first is load power factor (pf). Next in order (from left to right) are the exponents for the voltage (α_v , α_f) and frequency (β_v , β_f) dependencies associated with real and reactive power, respectively. N_m is the motor-load portion of the load. For example, both a refrigerator and a freezer are 80% motor load. Next in order are the power factor (pf_{nm}) and voltage (α_{vnm} , α_{fnnm}) and frequency (β_{vnm} , β_{fnnm}) parameters for the nonmotor portion of the load. Since the refrigerator and freezer are 80% motor loads (i.e., $N_m = 0.8$), the nonmotor portion of the load must be 20%.

20.5.2 Polynomial Models

A polynomial form is often used in a Transient Stability program. The voltage dependency portion of the model is typically second order. If the nonlinear nature with respect to voltage is significant, the order can be increased. The frequency portion is assumed to be first order. This model is expressed as follows.

$$P = P_o \left[a_o + a_1 \left(\frac{V}{V_o} \right) + a_2 \left(\frac{V}{V_o} \right)^2 \right] [1 + D_p \Delta f] \quad (20.6)$$

$$Q = Q_o \left[b_o + b_1 \left(\frac{V}{V_o} \right) + b_2 \left(\frac{V}{V_o} \right)^2 \right] [1 + D_q \Delta f] \quad (20.7)$$

TABLE 20.3 Parameters for Voltage and Frequency Dependencies of Static Loads

Component/Parameters	pf	α_v	α_f	β_v	β_f	N_m	pf_{nm}	α_{vnm}	α_{fnm}	β_{vnm}	β_{fnm}
Resistance Space Heater	1.0	2.0	0.0	0.0	0.0	0.0	—	—	—	—	—
Heat Pump Space Heater	0.84	0.2	0.9	2.5	−1.3	0.9	1.0	2.0	0.0	0.0	0.0
Heat Pump/Central A/C	0.81	0.2	0.9	2.5	−2.7	1.0	—	—	—	—	—
Room Air Conditioner	0.75	0.5	0.6	2.5	−2.8	1.0	—	—	—	—	—
Water Heater & Range	1.0	2.0	0.0	0.0	0.0	0.0	—	—	—	—	—
Refrigerator & Freezer	0.84	0.8	0.5	2.5	−1.4	0.8	1.0	2.0	0.0	0.0	0.0
Dish Washer	0.99	1.8	0.0	3.5	−1.4	0.8	1.0	2.0	0.0	0.0	0.0
Clothes Washer	0.65	0.08	2.9	1.6	1.8	1.0	—	—	—	—	—
Incandescent Lighting	1.0	1.54	0.0	0.0	0.0	0.0	—	—	—	—	—
Clothes Dryer	0.99	2.0	0.0	3.3	−2.6	0.2	1.0	2.0	0.0	0.0	0.0
Colored Television	0.77	2.0	0.0	5.2	−4.6	0.0	—	—	—	—	—
Furnace Fan	0.73	0.08	2.9	1.6	1.8	1.0	—	—	—	—	—
Commercial Heat Pump	0.84	0.1	1.0	2.5	−1.3	0.9	1.0	2.0	0.0	0.0	0.0
Heat Pump Comm. A/C	0.81	0.1	1.0	2.5	−1.3	1.0	—	—	—	—	—
Commercial Central A/C	0.75	0.1	1.0	2.5	−1.3	1.0	—	—	—	—	—
Commercial Room A/C	0.75	0.5	0.6	2.5	−2.8	1.0	—	—	—	—	—
Fluorescent Lighting	0.90	0.08	1.0	3.0	−2.8	0.0	—	—	—	—	—
Pump, Fan, (Motors)	0.87	0.08	2.9	1.6	1.8	1.0	—	—	—	—	—
Electrolysis	0.90	1.8	−0.3	2.2	0.6	0.0	—	—	—	—	—
Arc Furnace	0.72	2.3	−1.0	1.61	−1.0	0.0	—	—	—	—	—
Small Industrial Motors	0.83	0.1	2.9	0.6	−1.8	1.0	—	—	—	—	—
Industrial Motors Large	0.89	0.05	1.9	0.5	1.2	1.0	—	—	—	—	—
Agricultural H ₂ O Pumps	0.85	1.4	5.6	1.4	4.2	1.0	—	—	—	—	—
Power Plant Auxiliaries	0.80	0.08	2.9	1.6	1.8	1.0	—	—	—	—	—

where $a_o + a_1 + a_2 = 1$

$b_o + b_1 + b_2 = 1$

$D_p \equiv$ real power frequency damping coefficient, per unit

$D_q \equiv$ reactive power frequency damping coefficient, per unit

$\Delta f \equiv$ frequency deviation from scheduled value, per unit

The per-unit form of Eqs. (20.6) and (20.7) is the following.

$$P_u = \frac{P}{P_o} = \left[a_o + a_1 \left(\frac{V}{V_o} \right) + a_2 \left(\frac{V}{V_o} \right)^2 \right] [1 + D_p \Delta f] \quad (20.8)$$

$$Q_u = \frac{Q}{P_o} = \frac{Q_o}{P_o} \left[b_o + b_1 \left(\frac{V}{V_o} \right) + b_2 \left(\frac{V}{V_o} \right)^2 \right] [1 + D_q \Delta f] \quad (20.9)$$

20.5.3 Combined Exponential and Polynomial Models

The two previous kinds of models may be combined to form a synthesized static model that offers greater flexibility in representing various load characteristics (EPRI, 1987; Price et al., 1988). The mathematical expressions for these per-unit models are the following.

$$P_u = \frac{P_{poly} + P_{exp1} + P_{exp2}}{P_o} \quad (20.10)$$

$$Q_u = \frac{Q_{poly} + Q_{exp1} + Q_{exp2}}{P_o} \quad (20.11)$$

TABLE 20.4 Static Load Frequency Damping Characteristics

Component	Frequency Parameters	
	D _p	D _q
Three-Phase Central AC	1.09818	−0.663828
Single-Phase Central AC	0.994208	−0.307989
Window AC	0.702912	−1.89188
Duct Heater w/blowers	0.528878	−0.140006
Water Heater, Electric Cooking	0.0	0.0
Clothes Dryer	0.0	−0.311885
Refrigerator, Ice Machine	0.664158	−1.10252
Incandescent Lights	0.0	0.0
Florescent Lights	0.887964	−1.16844
Induction Motor Loads	1.6	−0.6

where

$$P_{\text{poly}} = a_0 + a_1 \left(\frac{V}{V_o} \right) + a_3 \left(\frac{V}{V_o} \right)^2 \quad (20.12)$$

$$P_{\text{exp1}} = a_4 \left(\frac{V}{V_o} \right)^{\alpha_1} [1 + D_{p1} \Delta f] \quad (20.13)$$

$$P_{\text{exp2}} = a_5 \left(\frac{V}{V_o} \right)^{\alpha_2} [1 + D_{p2} \Delta f] \quad (20.14)$$

The expressions for the reactive components have similar structures. Devices used for reactive power compensation are modeled separately.

The flexibility of the component models given here is sufficient to cover most modeling needs. Whenever possible, it is prudent to compare the computer model to measured data for the load.

Table 20.4 provides typical values for the frequency damping characteristic, D , that appears in Eqs. (20.6) through (20.9), (20.13), and (20.14) (EPRI, 1979). Note that nearly all of the damping coefficients for reactive power are negative. This means that as frequency declines, more reactive power is required which can cause an exacerbating effect for low-voltage conditions.

20.5.4 Comparison of Exponential and Polynomial Models

Both models provide good representation around rated or nominal voltage. The accuracy of the exponential form deteriorates when voltage significantly exceeds its nominal value, particularly with exponents (α) greater than 1.0. The accuracy of the polynomial form deteriorates when the voltage falls significantly below its nominal value when the coefficient a_o is non zero. A nonzero a_o coefficient represents some portion of the load as constant power. A scheme often used in practice is to use the polynomial form, but switch to the exponential form when the voltage falls below a predetermined value.

20.5.5 Devices Contributing to Modeling Difficulties

Some load components have time-dependent characteristics that must be considered if a sequence of studies using static models is performed that represents load changing over time. Examples of such a study include Voltage Stability and Transient Stability. The devices that affect load modeling by contributing abrupt changes in load over periods of time are listed below.

Protective Relays—Protective relays are notoriously difficult to model. The entire load of a substation can be tripped off line or the load on one of its distribution feeders can be tripped off line as a result of

protective relay operations. At the utilization level, motors on air conditioner units and motors in many other residential, commercial, and industrial applications contain thermal and/or over-current relays whose operational behavior is difficult to predict.

Thermostatically Controlled Loads—Air conditioning units, space heaters, water heaters, refrigerators, and freezers are all controlled by thermostatic devices. The effects of such devices are especially troublesome to model when a distribution load is reenergized after an extended outage (cold-load pickup). The effect of such devices to cold-load pickup characteristics can be significant.

Voltage Regulation Devices—Voltage regulators, voltage controlled capacitor banks, and automatic LTCs on transformers exhibit time-dependent effects. These devices are present at both the bulk power and distribution system levels.

Discharge Lamps (Mercury Vapor, Sodium Vapor, and Fluorescent Lamps)—These devices exhibit time-dependent characteristics upon restart, after being extinguished by a low-voltage condition—usually about 70% to 80% of rated voltage.

20.6 Load Window Modeling

The static load models found in [Tables 20.1](#) and [20.2](#) can be used to define a composite load referred to as the “load window” mentioned earlier. In this scheme, a distribution substation load or one of its feeder loads is defined in as much detail as desired for the model. Using the load window scheme, any number of load windows can be defined representing various composite loads, each having as many load components as deemed necessary for accurate representation of the load. Figure 20.2 illustrates the load window concept. The width of each subwindow denotes the percentage of each load component to the total composite load.

Construction of a load window requires certain load data be available. For example, load saturation and load diversity data are needed for various classes of customers. These data allow one to (1) identify the appropriate load components to be included in a particular load window, (2) assign their relative percentage of the total load, and (3) specify the diversified total amount of load for that window. If load modeling is being used for Transient Stability or Operator Training Simulator programs, frequency dependency can be added. Let $P(V)$ and $Q(V)$ represent the composite load models for P and Q , respectively, with only voltage dependency (as developed using components taken from [Tables 20.1](#) and [20.2](#)). Frequency dependency is easily included as illustrated below.

$$P = P(V) \times (1 + D_p \Delta f)$$

$$Q = Q(V) \times (1 + D_q \Delta f)$$

[Table 20.5](#) shows six different composite loads for a summer season in the southwestern portion of the U.S. This “window” serves as an example to illustrate the modeling process. Note that each column must

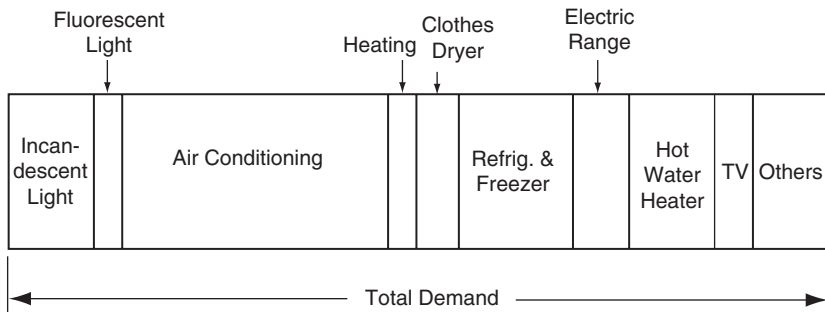


FIGURE 20.2 A typical load window with % composition of load components.

TABLE 20.5 Composition of Six Different Load Window Types

	LW 1	LW 2	LW 3	LW 4	LW 5	LW 6
Load Window Type	Res. 1	Res. 2	Res. 3	Com 1	Com 2	Indust
Load Component	(%)	(%)	(%)	(%)	(%)	(%)
3-Phase Central AC	25	30	10	35	40	20
Window Type AC	5	0	20	0	0	0
Duct Heater with Blower	5	0	0	0	0	0
Water Heater, Range Top	10	10	10	0	0	0
Clothes Dryer	10	10	10	0	0	0
Refrigerator, Ice Machine	15	15	10	30	0	0
Incandescent Lights	10	5	10	0	0	0
Fluorescent Lights	20	30	30	25	30	10
Industrial (Induct. Motor)	0	0	0	10	30	70

add to 100%. The entries across from each component load for a given window type represent the percentage of that load making up the composite load.

References

- EPRI User's Manual—Extended Transient/Midterm Stability Program Package*, version 3.0, June 1992.
- General Electric Company, Load modeling for power flow and transient stability computer studies, *EPRI Final Report EL-5003*, January 1987 (four volumes describing LOADSYN computer program).
- Kundur, P., *Power System Stability and Control*, EPRI Power System Engineering Series, McGraw-Hill, Inc., 271–314, 1994.
- Price, W.W., Wirgau, K.A., Murdoch, A., Mitsche, J.V., Vaahedi, E., and El-Kady, M.A., Load Modeling for Power Flow and Transient Stability Computer Studies, *IEEE Trans. on Power Syst.*, 3(1), 180–187, February 1988.
- Taylor, C.W., *Power System Voltage Stability*, EPRI Power System Engineering Series, McGraw-Hill, Inc., 67–107, 1994.
- University of Texas at Arlington, Determining Load Characteristics for Transient Performances, *EPRI Final Report EL-848*, May 1979 (three volumes).
- University of Texas at Arlington, Effect of Reduced Voltage on the Operation and Efficiency of Electrical Loads, *EPRI Final Report EL-2036*, September 1981 (two volumes).
- University of Texas at Arlington, Effect of Reduced Voltage on the Operation and Efficiency of Electrical Loads, *EPRI Final Report EL-3591*, June 1984 and July 1985 (three volumes).
- Warnock, V.J. and Kirkpatrick, T.L., Impact of Voltage Reduction on Energy and Demand: Phase II, *IEEE Trans. on Power Syst.*, 3(2), 92–97, May 1986.